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Abstract

We present two indirect drive inertial fusion targets driven by heavy ions beams for fusion energy production. Because there are uncertainties in the ion beam focal spot size and uncertainties in the accelerator cost, we have tried to design targets that cover a large parameter space. One of the designs requires small ion beam focal spots but produces more than adequate gain at low driver energy (gain 130 from 3.3 MJ of beam energy). The other design allows a large beam spot, but requires more driver energy (gain 55 from 6.7 MJ of beam energy). Target physics issues as well as the implications for the accelerator from each design are discussed.

1 Introduction

An accelerator producing beams of heavy ions is an attractive choice for an inertial fusion energy power plant because accelerators have the high repetition rate, long lifetime, and high efficiency needed for energy production. Because accelerators have high efficiency ($\eta > 25\%$), relatively modest target gains (~ 40) give an efficiency gain product greater than 10 ($\eta G > 10$) that is needed to keep the recirculating power fraction low. These modest gains can be achieved using indirect drive targets and allow us to leverage off of the investment made in indirect drive targets driven by lasers.

Over the past several years, we have explored a variety of targets driven by heavy ions. In particular, we have designed a "close-coupled" target that requires small ion beam focal spots but produces relatively high gain at low driver energy (gain 130 from 3.3 MJ of beam energy). Another design (the "hybrid" target) allows relatively large beam spots, but requires more driver energy (gain 55-60 at 6.7 MJ of beam energy). The reason for exploring such a diverse set of targets is that there is uncertainty in the both the ion beam dynamics and the cost of the driver so that there is still some uncertainty on where the optimum lies in parameter space. To cover this uncertainty, we have tried to design targets that cover a broad range of beam parameters.

2 The Close Coupled Target

The close-coupled target design has been documented in several papers [1, 2] so we will only briefly review it here.

The close-coupled target design grew out of our previous "distributed radiator" targets. In this type of target, symmetry is controlled by placing the radiation converters (which convert the beam energy into x-rays) near the zeros of the fourth Legendre polynomial. This results in two "rings" per side (regions C and F in Figure 1), similar to the two cones per side in the National Ignition Facility targets[3, 4]. Because this geometry allows for good symmetry control, we were able to reduce the case to capsule ratio and improve the coupling between the energy delivered by the driver and the amount of energy absorbed by the capsule. This resulted in relatively high gain (gain 133) from a modest driver energy (3.3 MJ of ion beam energy) in 2-d integrated Lasnex[5] calculations.

To achieve these results, we assumed the ion beam could be focused to an elliptical spot with semi major and semi minor axes of 2.8 mm by 1 mm. The ion beam distribution was assumed to be Gaussian at best focus and this ellipse is the one that contains 95% of the charge. The Lasnex calculations assumed the ion beams entered the target in two cones–one at 6 degrees and one at 12 degrees. To control symmetry, the kinetic energy of the ions is changed between the foot of the pulse and the main part of the pulse. This is accomplished by using different sets of beams for the foot and the main pulse. The Lasnex calculations assumed that the foot was driven by 2.2 GeV Pb^+ ions in the 6 degree cone and the main pulse was driven by 3.5 GeV Pb^+ ions in the 12 degree cone.

2.1 Issues with the Close-Coupled Target

One of the key features in the close-coupled target (and the distributed radiator target, as well) is the use of pressure balance between different density low Z and high Z materials. Rather than start with full density materials which then expand, we start with low density materials and try to minimize motion which can cause swings in the symmetry. For example, the hohlraum wall (region A in Figure 1) begins at density 0.1 g/cc and is held in place by density 0.01 g/cc plastic (region D in Figure 1). Fabrication of these low density, high Z materials is being researched; one option may be to use a collection of thin wires or thin sheets of material which is heated by a low power ion beam and allowed to expand to form the desired density.

The most important feature of this target from the ion beam perspective is the small focal spot. While the beam emittance in the source is smaller than needed to hit this spot, it may be difficult to maintain the required emittance through the accelerator, final focus, and chamber. In addition, hitting this spot will require very good beam neutralization in the chamber. In addition to requiring a small spot, this target also requires precise beam pointing. Recent viewfactor calculations[6] suggest pointing tolerances of about +/- 100 microns will be needed. The payoff for achieving small spots and accurate pointing is the small driver required.

3 The Hybrid Target

In order cover more of the available parameter space, we have designed a new heavy ion target that allows a large beam spot. This target is a hybrid between the distributed radiator target[7, 8, 9] and the end radiator target[10] (thus the name "hybrid") and allows a beam spot radius comparable to the hohlraum radius. Figure 2 shows the geometry of the hybrid target. The capsule used in this design is the same as the capsule used in the close-coupled target [1, 2].

Two-dimensional, integrated Lasnex calculations of the hybrid target produce 370 MJ of yield from 6.7 MJ of beam energy (1-d yield for this pulse shape is 410 MJ). These calculations assume the beams have a Gaussian distribution and are elliptical with semi-major and semi-minor axes of 5.4 by 3.8 mm (this ellipse holds 95% of the charge). Although elliptical beams were used in these calculations, it may be possible to use round beams with this design and future work will address this. As in the close-coupled target, the ion kinetic energy is changed between the foot of the pulse and the main pulse. In the calculation, the foot beams were assumed to be 3 GeV Pb^+ ions in a 6 degree cone. The main pulse was assumed to be 4.5 GeV Pb^+ ions in a 12 degree cone.

The notable features of this target are the internal shields used to control symmetry. Most of the beam energy is deposited behind a shine shield (region J in Figure 2) and radiation flows around the shine shield. The end result is that the capsule sees a bright source above the shine shield which results in a significant P_4 asymmetry. This is corrected using a shim (region P in Figure 2)–a thin layer of iron placed on or near the capsule surface to block the excess energy.

3.1 Issues with the Hybrid Target

Physics issues in the hybrid target include accurate calculation of hydrodynamic motion of the converter material and shine shield, accurate knowledge of the ion range, limits on the allowable beam angles, and the effect of the shim on the Rayleigh-Taylor instability.

In the hybrid target, pressure balance of the converter material had to be abandoned if we wanted to stop the ions behind the shine shield without increasing the hohlraum length. Increasing the hohlraum length would result in an additional energy penalty that we wanted to avoid. The end result is that the both the converter and the shine shield expand radially during the pulse. If the shine shield expands too much, it blocks the path for radiation flow and results in poor coupling. If the converter expands too much, it intercepts more and more of the ions that are aimed above the shine shield and results in symmetry swings.

In the close-coupled target, the ion beam is aimed toward that hohlraum wall and away from the capsule which made the target insensitive to small errors in ion range. In contrast, the hybrid target has the ion beam aimed directly at the capsule and small errors in ion range can result in ions impacting the capsule. This must be avoided and so it is important to know the ion range (as a function of temperature and density) well for this target.

Another issue for the hybrid target is what are the allowable beam angles. Because the shine shield has to be large enough to protect the capsule, an increase in the beam angles will mean that a larger shine shield is needed. Using a larger shine shield will mean that more beam energy is deposited behind the shield and make symmetry harder to achieve. A larger shine shield will increase the risk of having the gap between the shine shield and the wall close up as the shield expands during the pulse. In fact, the shine shield used in the integrated calculations was only big enough to protect the capsule from the 6 degree beams at time zero, when the target is cold and the ion range is long. The design used the fact that the ion range would be shorter and the shine shield would have expanded by the time the 12 degree cone of beams turned on in the main pulse.

The hybrid target uses a shim layer to correct the P_4 asymmetry. In the integrated calculations, the shim was made up of a 200 micron thick layer of density 0.01 g/cc iron foam placed on the surface of the capsule. Placing the shim layer on the capsule can cause a perturbation which seeds the Rayleigh-Taylor instability. Capsule only calculations are now in progress to minimize the effect of the shim on the Rayleigh-Taylor instability.

The payoff for the target physics issues in the hybrid target is the large ion beam spot. Although the target requires more ion beam energy (6.7 MJ vs 3.3 MJ for the close-coupled target), the large beam spot may allow lower energy, lower mass ions (with the same ion range) to be used. Lower energy ions require a shorter accelerator which is less expensive.

4 Conclusions

We have presented two indirect drive targets driven by heavy ion beams. One design, the close-coupled target, requires small ion beam focal spots ($\approx$ 1-2 mm radius) but gives a high gain at low driver energy (gain 133 at 3.3 MJ beam energy). The second design, the hybrid target, allows a large ion beam focal spot ($\approx$ 4-5 mm radius) but requires more driver energy (gain 55 at 6.7 MJ beam energy). Because there are uncertainties in the beam dynamics that will determine the final beam spot size, and because there are uncertainties in the cost of the accelerator, it is unclear which of these targets will lead to the lowest cost option. As an example, because the hybrid target allows a large beam spot, it may be possible to use lower mass, lower kinetic energy ions (with the same ion range) and still focus to the required spot. Lower kinetic energy ions can be produced in a shorter accelerator, which is less expensive. As a result of uncertainties such as this, we have tried to design targets that cover as much of the parameter space as possible. In the end, an optimization of the entire system including accelerator, final focus, chamber, and target will be used to select the best choice.

5 Acknowledgements

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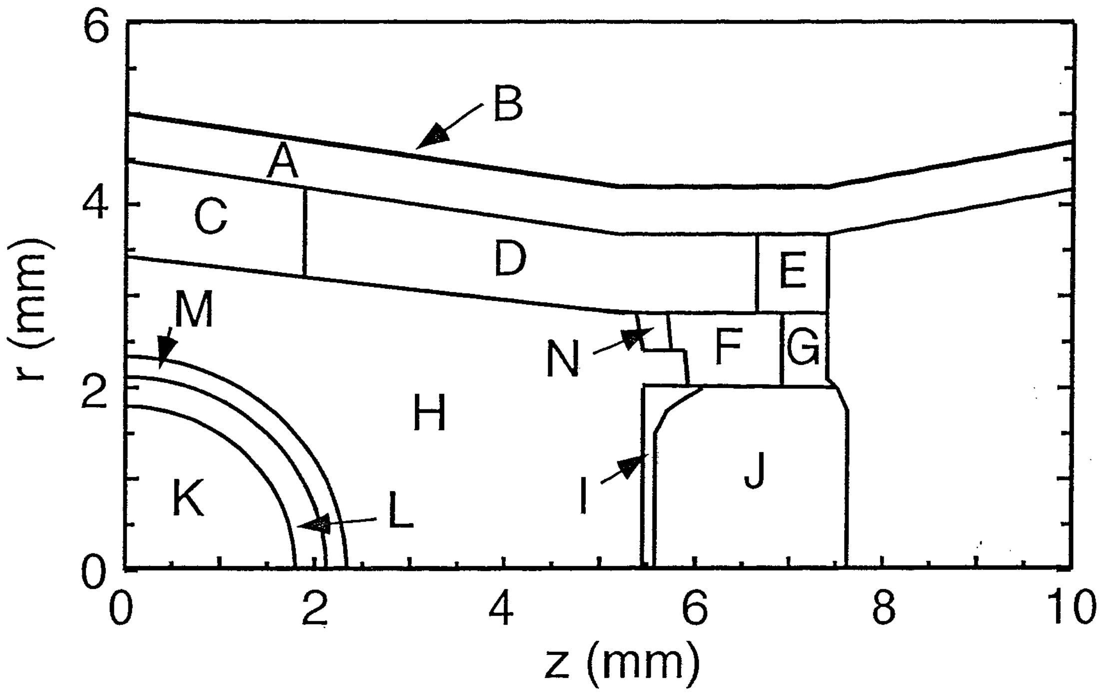

fig 1

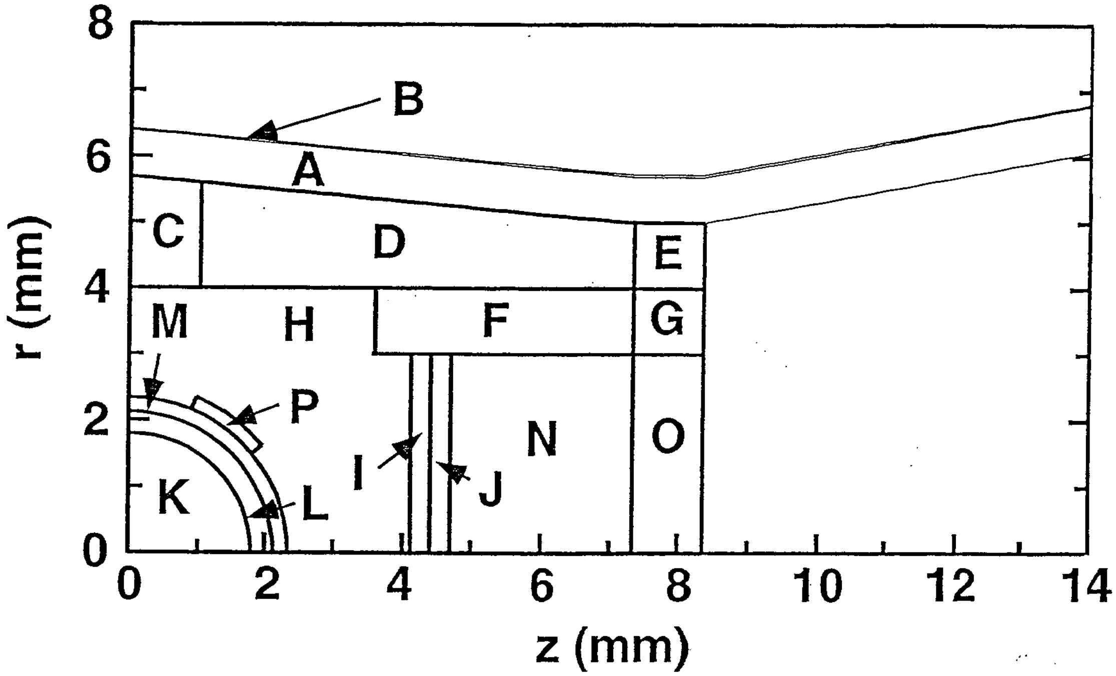

fig 2

Figure 1: A diagram of 1/4 of the capsule and hohlraum for the close-coupled target. The complete target is a rotation about the z-axis and a reflection about the r-axis. The materials and densities used were as follows: (A) AuGd at 0.1 g/cc, (B) 15 microns layer of AuGd at 13.5 g/cc, (C) Fe at 16 mg/cc, (D) $(CD_2)_{0.97}Au_{0.03}$ at 11 mg/cc, (E) AuGd at 0.11 g/cc, (F) Al at 70 mg/cc, (G) AuGd at 0.26 g/cc, (H) CD_2 at 1 mg/cc, (I) Al at 55 mg/cc, (J) AuGd sandwich with densities 0.1 g/cc, 1.0 g/cc, and 0.5 g/cc, (K) DT at 0.3 mg/cc, (L) DT at 0.25 g/cc, (M) $Be_{0.995}Br_{0.005}$ at 1.845 g/cc, (N) $(CD_2)_{0.97}Au_{0.03}$ at 32 mg/cc.

Figure 2: A diagram of 1/4 of the capsule and hohlraum for the hybrid target. The complete target is a rotation about the z-axis and a reflection about the r-axis. The materials and densities used were as follows: (A) AuGd at 0.1 g/cc, (B) 15 microns layer of AuGd at 13.5 g/cc, (C) Au at 32 mg/cc, (D) $(CD_2)_{0.97}Au_{0.03}$ at 10 mg/cc, (E) AuGd at 0.1 g/cc, (F) $(CD_2)_{0.97}Au_{0.03}$ at 40 mg/cc, (G) AuGd at 0.1 g/cc (upper half) and 0.2 g/cc (lower half), (H) CD_2 at 1 mg/cc, (I) Al at 55 mg/cc (lower half) and 121 mg/cc (upper half), (J) Sn at 0.2 g/cc (lower half) and 0.3 g/cc (upper half), (K) DT at 0.3 mg/cc, (L) DT at 0.25 g/cc, (M) $Be_{0.995}Br_{0.005}$ at 1.845 g/cc, (N) Al at 0.145 g/cc, (O) AuGd at 0.1 g/cc, (P) Fe at 10 mg/cc.

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